AMBIENT RADON-222 MONITORING IN AMARGOSA VALLEY, NEVADA

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Abstract - *As part of a program to characterize and baseline selected environmental parameters in the region around the proposed repository at Yucca Mountain, Nevada, ambient radon-222 monitoring was conducted in the rural community of Amargosa Valley, the community closest to the proposed repository site. Passive integrating radon monitors and a continuous radon monitoring instrument were deployed adjacent to the Community Environmental Monitoring Program (CEMP) (http://www.cemp.dri.edu/index.html) station located in the Amargosa Valley Community Center near the library. The CEMP station provided real-time ambient gamma exposure and meteorological data used to correct the integrated radon measurements as well as verify meteorological data collected by the continuous radon monitoring instrument. Additionally, different types of environmental enclosures that housed the monitors and instrument were used to determine if particular designs influenced the ambient radon measurements.*

I. INTRODUCTION

In assessing the potential environmental impacts associated with the proposed repository at Yucca Mountain, NV, the Department of Energy (DOE) has identified radon-222, and its decay progeny, as the main radiological effluents from the facility[1,2]. In addition, DOE has indicated that exposure to these radioactive effluents could account for greater than 99 percent of potential health impacts to the maximally exposed individual (MEI) [1,2]. The MEI is a theoretical receptor who is located approximately 18 km (11 mi) south of the repository, in the general direction of Amargosa Valley, NV[2] .

In the early 1990s, the Nevada Bureau of Mines and Geology, Nevada Division of Health, and U.S. Environmental Protection Agency (EPA) conducted radon-222 monitoring throughout Nevada[3]. The program included measurements of both indoor and outdoor radon-222 concentrations employing passive integrating radon monitoring systems. Concurrent to this program, DOE through the Technical and Management Support Services contractor for the Yucca Mountain Site Characterization Project Office conducted a program to characterize the radiological environment in the vicinity of the proposed repository site[4]. The program included measurements of radon-222 from selected sites within the project site boundaries employing both passive integrating and continuous radon monitoring technologies[5,6] . Unfortunately, neither of the earlier programs monitored radon concentrations in Amargosa Valley. In April 2007, the Desert Research Institute (DRI) initiated an ambient radon monitoring program in Amargosa Valley with the intent of filling this data gap.

II. AMARGOSA VALLEY

Amargosa Valley is an unincorporated town that was founded in 1905 to support the Borax mines in the area. Amargosa is a Spanish word for bitter water, and Amargosa Valley is located in the northern part of the Mojave Desert on a playa at an elevation of 811 m (2,661 ft), 56 km (35mi) south of Yucca Mountain. The town covers an area of 877 sq/km (545 sq/mi) and has a population of 1,350 (Figure 1). There are three dairies in the valley, which produce approximately 40 percent of all the milk produced in Nevada. The Ponderosa Dairy has 20,000 cows, 9,500 of which are milked daily. The milk from these dairies goes into a system that reaches as far north as the state of Washington and as many as 70 million people. Mining is ongoing in the area and plants have been built for processing cinder and specialty clay products. Future economic possibilities for the Amargosa Valley include solar power production.

III. EQUIPMENT AND METHODOLOGY

Initially, DRI selected three passive radon monitoring systems, the Electret Passive Environmental Radon Monitor (E-PERM®) by Rad Elec, Inc., RadTRAK® system by Landauer, Inc., and the AlphaGUARD® by Genitron, Inc.

The E-PERM® system is a passive system that consists of a monitor and a reader. The monitor consists of a conductive plastic air ionization chamber and an electrically charged Teflon® disk. Air, containing radon-222, diffuses into the chamber through a small filtered opening. As the radon-222 and its progeny decay, the air in the chamber ionizes and negative ions are attracted to the charged Teflon®, disk resulting in an

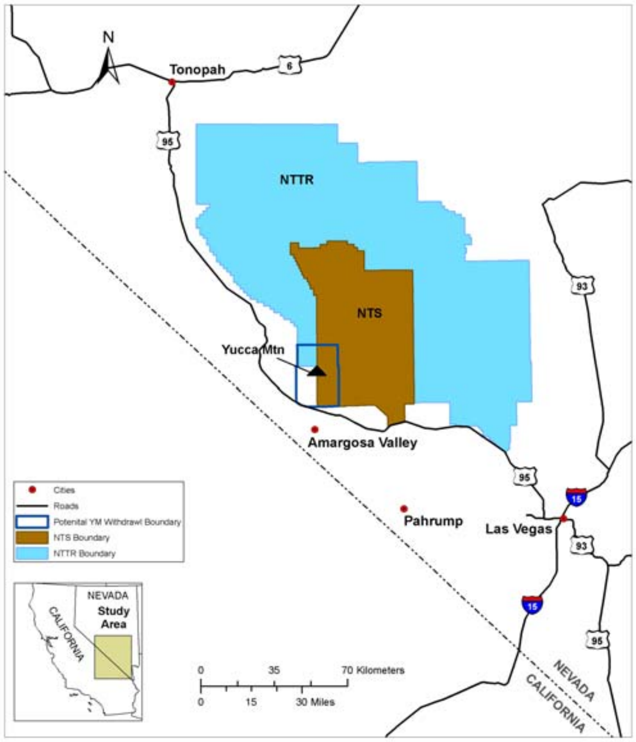

Figure 1. Location Map of Amargosa Valley

electrical discharge on the disk that is proportional to the ion concentration and the exposure time. Positively charged ions are attracted to the plastic walls of the chamber and are neutralized. The voltage on the Teflon® disk is read and recorded before and after deployment. The voltage difference is entered into manufacturer supplied software and the corresponding radon-222 concentrations are calculated. The E-PERM® systems are sensitive to dust, which may cause excessive discharging, and are placed in gas-permeable Tyvex bags to prevent this. They also require protection from the weather, which was accomplished through the use of a well-ventilated enclosure. The estimated minimum measurable concentration for a multi-week deployment is approximately 4Bq/m^3 (0.1 pCi/l).

The RadTRAK® passive integrating system uses a radiosensitive material, ally diglycol carbonate, commonly called CR-39. The CR-39 is contained in plastic casing with a filtered opening, which allows radon-222 to diffuse into the casing. As the radon decays, the emitted alpha particles penetrate the CR-39, leaving a track as the alpha particle travels into the material. At the end of the deployment period, the RadTRAK® is returned to the manufacturer for processing. Since these detectors require protection from meteorological conditions, they were placed in protective shelters. The RadTRAK® system has a reported minimum level of detection for radon-222 of 1,111 Bq/m^3-days (30 pCi/L-days), based on an exposure period of 90 days at a concentration of approximately 11Bq/m^3 (0.3pCi/l) (http///ldrsolutions.landauerinc.com; accessed 02-07-08).

The AlphaGUARD System (AGS) was selected as the continuous radon monitoring instrument, which utilizes the pulse-ionization measurement technique and requires AC electrical power. Similar to the E-PERM® passive system, radon-222 diffuses through a fiber glass filter into a 0.56-liter counting chamber. The filter diffusion characteristics are designed to limit diffusion in to allow for the decay of radon-220 (half-life of approximately 56 seconds), a progeny of the naturally occurring radioisotope thorium-232. As the radon-222 and progeny decay, the air is ionized and the ions are attracted to either the cathode or the anode, producing an electrical pulse. The pulse is then post-processed via a series of algorithms. Radon measurements are made at a set frequency and average concentrations are recorded at either 10- or 60-min intervals, which are set by the user. The data storage capabilities of the instrument are limited and the instrument will start to overwrite the data if it is not downloaded regularly. Amargosa Valley is over 161 km (100 mi) from the DRI office in Las Vegas and downloading the data was scheduled to coincide with other work at the CEMP station, which is performed monthly, necessitating a 60-min interval. The AGS is the size of a large hand-held instrument and along with the chamber houses a set of meteorological sensors for air temperature, relative humidity, and barometric pressure. The system has a lower limit of detection of less than 2 Bq/m^3 (0.05pCi/l)[7].

One of the challenges of this study was that none of the above instruments was designed to be placed directly into the environment. A weather enclosure was needed that provided AC power and protection from the elements yet allowed the ambient movement of radon gasses around the instruments without overly influencing the gasses. Essentially, the enclosure could not be a radon trap, causing higher than actual readings, or induce unnatural air flow, diluting the sample. The CEMP has two sizes of weather enclosures, one used to house air sampling equipment and the other for an older style windup microbarograph. The enclosures are nick-named doghouses because of their size and shape. Two of the enclosures were borrowed from the CEMP. The larger doghouse was taken apart, extra louvers added to the sides and the doors of the doghouse, and the unit reassembled. A secondary floor was built from wood and plastic screen, allowing the E-PERMs® to be held in groups above the doghouse floor, further promoting the E-PERM's exposure to ambient air. The smaller doghouse did not have a floor so a screen floor was added and vent holes installed at the top of the sides of the doghouse. The entire unit was then painted with white roofing paint to reflect sunlight in an effort to keep the internal temperature as close to the ambient as possible. If the internal temperature of the doghouse becomes considerably warmer than the ambient temperature, one of two things can happen: 1) high pressure can build in the enclosure, keeping the radon gasses out, or 2) convection can begin and more air pulled through the enclosure than the actual ambient air movement at the time.

IV. FIELD INTER-COMPARISON PASSIVE INTEGRATING RADON MONITORING SYSTEMS

The passive integrating systems were deployed in Amargosa Valley during the second quarter of 2006 (April – July). Three E-PERMs® and three RadTRAK® sensors, each placed in Tyvex bags, were deployed in the larger modified doghouse approximately 1 m above the ground. A second set of RadTRAK® sensors was deployed in environmental enclosures purchased from the manufacturer. At the end of the quarter, the RadTRAK® sensors were returned to the manufacturer for analysis. The three sensors placed in the manufactured enclosures and one in the doghouse shelter had alpha tracks that were "oversized and looked like bubbles"[8] , which is abnormal, and about which the manufacture had no plausible explanation. The remaining two from the doghouse showed radon concentrations between 14.8 and 18.5 Bq/m^3 (0.4 and 0.5 pCi/l). Because of these response uncertainties, the use of the RadTRAK® sensors was suspended and focus placed on the E-PERMs® and AlphaGUARD®.

The E-PERM® measurements for the same period indicated an average ambient Rn concentration of 11.1 ± 3.7 Bq/m^3 (0.3 ± 0.1 pCi/l).

V. GAMMA EXPOSURE CORRECTION FOR E-PERM® RADON CONCENTRATION MEASUREMENTS

Because the E-PERM® sensors function as air ionization chambers, radon measurements must be corrected for effect of background gamma exposure. The manufacturer, Rad Elec, Inc., recommends two correction methods. The first uses a radon concentration equivalent gamma exposure rate factor that can be applied to a corresponding site-specific average exposure rate or to site-specific exposure rates measured in the monitoring location. The second involves measuring the effect of ambient gamma on the E-PERM® using additional E-PERMs®.

Rad Elec, Inc., provides generic average gamma exposure rates for all the states in the U.S.[9] For Nevada, they list two gamma exposure rates, 61 nSv (6.1 µR/hr) for lower elevations and 121 nSv (12.1 µR/hr) for higher elevations. However, collocating with the CEMP station provides a comprehensive list of background gamma readings during deployment as well as an extensive historical record.

The radon concentration equivalent gamma exposure rate factor varies as a function of the E-PERM® chamber deployed. Measurements in Amargosa Valley utilized 210-ml "S"-chambers that had an associated radon concentration equivalent gamma exposure rate factor of 3.2Bq/m^3 per nSv/hr (0.087 pCi/L per µR/hr)[9]. This factor was multiplied by the ambient gamma exposure rate for the measurement site, and the resulting number was subtracted from the calculated radon concentration.

VI. CONTINUOUS RADON MONITORING SYSTEM

To assess the accuracy of the environmental parameter sensors of the AGS, and to determine if the conditions in the shelter were significantly different from ambient conditions, mean temperature, barometric pressure, and relative humidity values were calculated for specific measurement periods and compared with the same summary statistics available for the CEMP station in Amargosa Valley. The criterion selected for use was whether or not the difference between the mean AGS value for the parameter and the mean CEMP value for the parameter fell outside the range of Initial Calibration Uncertainty (ICU) value for the AGS parameter sensor as provided by the manufacturer. The ICU values for temperature, barometric pressure, and relative humidity are ± 1.5 ^{o}C, ± 3 mbar, and ± 3 percent rH, respectively[7]. The results of these comparisons are presented in Tables 1, 2, and 3.

The results of the comparison indicate that in measuring barometric pressure, as configured, the difference between the AGS mean value and the CEMP mean value for the measurement periods was within the ICU value for the AGS, suggesting that the AGS sensor was accurate, and that the configuration did not significantly effect the measurement. Measurement of relative humidity showed a similar trend with the difference in mean values falling within the ICU values for eight out of nine periods, with the difference between the values for the ninth measurement period being slightly above the ICU value, i.e., 4 percent versus 3 percent.

The measurement period mean temperature, as calculated from the AGS data, was consistently higher than that calculated for the CEMP station. The differences between the AGS mean temperature values and the CEMP mean temperature values exceeded the ICU for temperature for three out of nine measurement periods, with the differences exceeding the ICU by more than 50 percent two out of three times. These trends suggest a potential influence of the shelter on the measurement of temperature.

Table 1. Temperature measurement comparison, CEMP and AGS.

Measurement Period	CEMP Mean Temperature (^{o}C)	AGS Mean Temperature (^{o}C)	Measurement Delta (AGS – CEMP)
4/4 – 5/8/2007	19.3	20.7	1.4
5/9 – 6/6/2007	26.4	27.9	1.5
6/7 – 7/10/2007	30.3	32.8	2.5
7/11 – 8/7/2007	32.2	33.0	0.8
8/8 – 9/4/2007	31.8	33.9	2.1
9/5 – 10/2/2007	23.8	25.0	1 .2
10/3 – 11/3/2007	17.5	18.8	1.3
11/4 – 12/04/2007	12.0	12.7	0.7
12/5/07 – 1/08/2008	5.3	6.3	1

Table 2. Mean barometric pressure comparison, CEMP and AGS.

Measurement Period	CEMP Mean Barometric Pressure (mbar)	AGS Mean Barometric Pressure (mbar)	Measurement Delta (AGS – CEMP)
4/4 – 5/8/2007	924.5	927.9	3.4
5/9 – 6/6/2007	924.5	924.5	0
6/7 – 7/10/2007	924.5	924.5	0
7/11– 8/7/2007	927.9	924.5	3.4
8/8 – 9/4/2007	924.5	927.9	3.4
9/5 – 10/2/2007	927.9	932.3	3.4
10/3 – 11/3/2007	931.3	931.3	0
11/4 – 12/4/2007	931.3	931.3	0
12/5/07 – 1/08/2008	931.3	934.6	3.3

Table 3. Mean relative humidity comparison, CEMP and AGS.

Measurement Period	CEMP Mean Relative Humidity (%)	AGS Mean Relative Humidity (%)	Measurement Delta (AGS – CEMP) (%)
4/4 – 5/8/2007	21	21	0
5/9 – 6/6/2007	12	12	0
6/7 – 7/10/2007	10	10	0
7/11 – 8/7/2007	20	19	-1
8/8 – 9/4/2007	18	18	0
9/5 – 10/2/2007	26	25	-1
10/3 – 11/3/2007	26	27	-1
11/4 – 12/4/2007	34	33	-1
12/5/07 – 1/08/2008	45	41	-4

VII. COMPARISON OF AMBIENT RADON-222 MEASUREMENTS

Since April 2007, approximately 10 months of ambient radon-222 concentration data have been collected in Amargosa Valley, NV, utilizing both passive integrating (~monthly) and passive continuous (hourly average) radon monitoring systems. Preliminary comparison of the data from the two systems shows a high degree of agreement between the average radon concentration measurement periods, as shown in Table 4.

Average radon concentrations, as measured by both systems, ranged from approximately 7.4 to 14.8 Bq/m^3 (0.2 to 0.4 pCi/l).

These average radon concentrations are consistent with the average radon concentration of 12.6 Bq/m^3 (0.34 pCi/l) reported for the period 1991 to 1995 for onsite monitoring stations in the vicinity of Yucca Mountain[10], and with the ambient radon measurement of 11.1 Bq/m^3 (0.30 pCi/l) reported for a location in the general area of Amargosa Valley during the early 1990s[11].

Table 4. Average radon-222 concentration plus/minus 1 Sigma (Bq/m^3).

Monitoring Period	Average Radon Conc. Bq/m^3 (pCi/l) (E-PERM®)	Average Radon Conc. Bq/m^3 (pCi/l) (AGS)
4/3 – 5/8/2007	11.1+/-3.7 (0.3 +/- 0.1)	6.7+/-4.4 (0.18 +/- 0.12)
5/8 – 6/6/2007	11.1+/-0 (0.3 +/- 0.0)	7.8+/-4.8 (0.21 +/- 0.13)++
6/6 – 7/10/2007	11.1+/-3.7 (0.3 +/- 0.1)	7.8+/-4.4 (0.21 +/- 0.12)
7/10 – 8/7/2007	7.4+/- 3.7 (0.2 +/- 0.1)	7.0+/-4.4 (0.19 +/- 0.12)
4/3 – 8/7/2007 (Qtr.)	7.4+/-3.7 (0.2 +/- 0.1)	7.4+/-4.4 (0.20 +/- 0.12)
8/7 – 9/4/2007	7.4+/-3.7 (0.2 +/- 0.1)	7.8+/-4.8 (0.21 +/- 0.13)
9/4 – 10/2/2007	7.4+/-3.7 (0.2 +/- 0.1)	7.4+/-4.8 (0.20 +/- 0.13)
10/2 – 12/4/2007	11.1+/-3.7 (0.3 +/- 0.1)	8.9+/-7.0 (0.33 +/- 0.19)
12/4/07 – 1/8/2008	14.8+/-3.7 (0.4 +/- 0.1)	13.3+/-9.6 (0.36 +/- 0.25)
10/2/07 – 1/8/2008 (Qtr.)	11.1+/-3.7 (0.3 +/- 0.1)	12.6+/-7.0 (0.34 +/- 0.19)
1/8/08 – 2/6/2008	11.1+/-3.7 (0.3 +/- 0.1)	10.4+/-6.7 (0.28 +/- 0.18) **
2/6/08 – 3/4/2008	14.8+/-3.7 (0.4 +/- 0.1)	N/A **

++ Unexplained time/data gap.

** Incomplete data set; nondetector-related equipment failure.

VIII. CORRELATION ANALYSES OF AGS ENVIRONMENTAL PARAMETER MEASUREMENTS WITH AMBIENT RADON-222 CONCENTRATION MEASUREMENTS

To identify potential relationships between the location-specific meteorological parameters, i.e., temperature, barometric pressure, and relative humidity, and ambient radon concentration, correlation coefficients (r) were calculated for each parameter, for each monitoring period, and for a day within that period. The results of these evaluations are presented in Tables 5 and 6, and indicate weak correlations between any one parameter and ambient radon concentration.

A consistent, but variable, positive correlation was found between average hourly radon concentrations and relative humidity over both the short-term (daily) and long-term (> 28 days), while a consistent inverse (weak negative) relationship was found between temperature and average hourly radon concentrations. A very weak correlation was found between barometric pressure and ambient radon concentration. Such relationships are consistent with those previously identified for ambient radon measurements made during the site characterization phase for Yucca Mountain[12]. The lack of any strong constant correlation between ambient radon concentration and any one parameter is consistent with the fact that multiple parameters influence ambient radon concentrations to varying extents.

IX. DISCUSSION

Desert Research Institute is evaluating three passive radon monitoring systems, two integrating and one continuous. Evaluation activities conducted during 2006 have shown that each system has distinct functional characteristics that affect the performance of the monitoring system. Early in the evaluation process, the AlphaTRAK®, exhibited unexpected alpha response characteristics that resulted in the suspension of the use of the system. The remaining systems, E-PERM® and AlphaGUARD®, were found to be reliable and accurate within their respective system limitations. However, each exhibited operational characteristics that placed limitations on their use in arid, rural areas.

The E-PERM® systems, because they are air ionization chambers, require that the effect of ambient gamma on the measurement be taken into account prior to determining radon-222 concentrations. Direct measurement of the ambient gamma component using E-PERMs®, with and without activated charcoal, was found to be inconsistent and unreliable. To accurately determine ambient radon-222 concentration, support of an ambient gamma measuring system, such as a high-pressure ionization chamber, was found to be required.

The E-PERMs®, as integrating monitoring devices, provide only a single time-averaged measurement and were found to require only protection from meteorological condition. These systems are designed basically as a "deploy-and-forget" system that requires no, or infrequent, checking during deployment. A review of the response characteristics of the E-PERMs, i.e., voltage decrease per day deployed, as a function of deployment time were found to be consistent, averaging a 3 volts/day decrease. This consistency allowed for flexibility in the length of deployment.

The AlphaGUARD® system, as a continuous monitoring system, allows for variable counting periods, either 10 or 60 min. Because the system utilizes a pulse ionization chamber and a series of post processing and/or seasonal variations in radon-222 concentration. In addition, the system also has the capability of monitoring

Table 5. Short-term relationships between ambient radon concentration and AGS meteorological parameter measurements.

	Correlation Coefficient (r)		
Date	Temperature (°C)	Pressure	Relative Humidity
4/16/2007	-0.26	-0.16	0.19
5/15/2007	-0.89	0.28	0.89
6/15/2007	-0.82	0.28	0.73
7/15/2007	-0.82	-0.09	0.39
8/15/2007	-0.81	0.58	0.90
9/15/2007	-0.70	0.56	0.79
10/15/2007	-0.79	0.57	0.85
11/15/2007	-0.34	-0.19	0.31
12/15/2007	-0.48	-0.20	0.41

Table 6. Long-term relationship between AGS environmental parameter measurements to ambient radon-222 concentration measurements.

	Correlation Coefficient (r)		
Measurement Period	Barometric Pressure	Temperature (°C)	Relative Humidity
4/3/07-5/8/2007	0.09	-0.24	0.18
5/8/07- 6/5/2007	0.19	-0.68	0.44
6/5/07 – 07/10/2007	0.17	-0.54	0.26
7/10/07 – 8/7/2007	0.23	-0.57	0.31
8/7/07 – 9/4/2007	0.10	-0.66	0.24
9/4/07 -10/2/2007	0.10	-0.34	0.00
10/2/07 – 12/4/2007	-0.06	-0.40	0.37
12/4/07 – 1/08/2007	0.04	-0.31	0.22

algorithms, it provides accurate and precise data. As such, the system allows for the monitoring of diurnal ambient environmental parameters in the immediate vicinity of the system, allowing for the evaluation of radon-222 concentration as a function of temperature, barometric pressure, and relative humidity. Comparison of mean barometric pressure and relative humidity values based on AGS measurements and those based on measurements made at the CEMP station showed a relatively high degree of agreement, with all but one mean value falling within the initial calibration uncertainty of the AGS sensors. For the AGS mean temperature values, approximately one-third of the values fell outside of the temperature sensor's initial calibration uncertainty, suggesting either a bias due to the "dog house". It is expected that subsequent data comparison and analyses will help clarify the cause of this deviation.

Review of the AGS data for the period April 2007 through January 2008, as recorded, indicates an overall hourly data collection efficiency of more than 99.6 percent, with only one period of 31 hourly periods not recorded due to unidentified cause(s). For the same period, the AGS internal status system reported that approximately 38 percent of the hourly average radon measurements were at or below the lower limit of detection. The association of the "at or below lower limit of detection" status indicator with environmental factors is currently being reviewed.

Comparison of the average ambient radon concentrations measured by the two systems revealed a high degree of consistency. Average radon concentrations ranged between 7.4 and 14.8 Bq/m^3 (0.2 and 0.4 pCi/l), with the average E-PERM® radon concentration falling consistently within the spread of the AGS measurements, i.e., within plus or minus one standard deviation. The consistency between the average radon concentrations measured by the two systems and their agreement with historical data on radon concentrations in the region around Amargosa Valley, NV, results in a high degree of confidence in accuracy of the measurements.

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XI. REFERENCES

1. DOE, U.S. DEPARTMENT OF ENERGY, Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada, Office of Civilian Radioactive Waste Management, DOE/EIS-0250 (February 2002).

2. DOE, 2007, U.S. DEPARTMENT OF ENERGY, Draft Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada, Office of Civilian Radioactive Waste Management, DOE/EIS-0250F-S1D (October 2007).

3. J.G. RIGBY, J.G. PRICE, L.G. CHRISTENSEN, D.D. LA POINTE, A.R. RAMELLI, M.O. DESILETS, R.H. HESS, and S.R. MARSHALL, Radon in Nevada, Nevada Bureau of Mines and Geology, University of Nevada, Reno, Bulletin 108 (1994).

4. DOE, U.S. DEPARTMENT OF ENERGY, Radiological Monitoring Plan for the NNWSI Project, Office of Civilian Radioactive Waste Management, Nevada Nuclear Waste Storage Investigations Project, Nevada Operations Office, DOE/NV-10576-6 (March, 1988).

5. M.D. GRIFFIN, "Active verses Passive Monitoring at the Yucca Mountain Site," Proceedings of the Fifth Annual International Conference on High Level Radioactive Waste Management, American Nuclear Society/American Society of Civil Engineers, Las Vegas , NV (1994).

6. N. LIU, C.D. SORENSEN, C.H. TUNG, and C.R. ORCHARD, "Continuous Environmental Radon Monitoring Program at the Yucca Mountain Site Characterization Project," Proceedings of the Sixth Annual International Conference on High Level Radioactive Waste Management, American Nuclear Society/American Society of Civil Engineers, Las Vegas , NV (1995).

7. GENITRON INSTRUMENTS GMBH, AlphaGUARD Portable Radon Monitor: User Manual (December 1998).

8. J.J. TAPPEN, Preliminary Draft Radon Monitoring Interim Report, Desert Research Institute (March 24, 2008).

9. RAD ELEC, INC., E-PERM® System Users Manual, Frederick, Maryland (2002).

10. TESS, TRW Environmental Safety Systems, Inc., Environmental Baseline File: Human Health, Civilian Radioactive Waste Management System, Management and Operating Contractor (March 1999).

11. J.G. PRICE, J.G. RIGBY, L. CHRISTENSEN, R. HESS, D.D. LAPOINTE, A.R. RAMELLI, M. DESILETS, R.D. HOPPER, T. KLUESNER, and S. MARSHALL, "Radon in Outdoor Air in Nevada," Health Physics, **66**(4): 433 – 438 (1994).

12. TESS, TRW Environmental Safety Systems, Inc., Update Report for Ambient Radon at the Yucca Mountain Site, Civilian Radioactive Waste Management System, Management and Operating Contractor (September 1998).